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MEASUREMENTS OF HEAT RELEASE RATES ON WOOD PRODUCTS AND AN ASSE--ETC(U)
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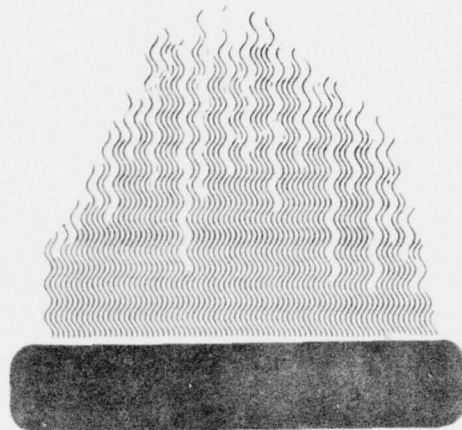
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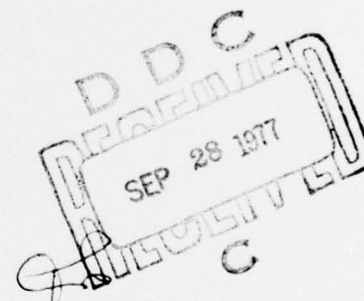


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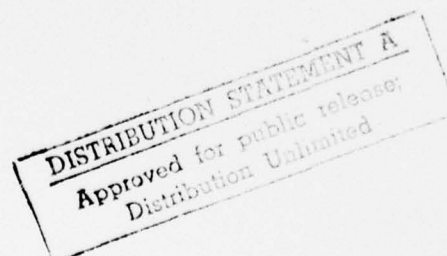
MEASUREMENTS OF HEAT RELEASE RATES ON WOOD PRODUCTS AND AN ASSEMBLY

USDA FOREST SERVICE
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ABSTRACT

For acceptance and safe use of wood and wood products in houses and other buildings, adequate methods should be available to measure their rate of heat release -- degree of combustibility. Data for wood and wood products and methods of improving these products should also be obtained. The work reported here is part of a series of heat release tests on identical samples that were sent to several laboratories to be tested by different sets of apparatus. The data discussed here were obtained and analyzed at the Forest Products Laboratory. Findings include the following: (1) Additional evidence that rate of heat release from wood can be reduced by treating wood with fire retardants, and (2) evidence that rate of heat release of a wall assembly cannot be easily deduced from the rate of heat release of assembly components.

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MEASUREMENTS OF HEAT RELEASE RATES ON WOOD PRODUCTS AND AN ASSEMBLY

By

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INTRODUCTION

Until recently, regulatory agencies via building codes attempted to prevent the propagation of fires in buildings by having "noncombustible" materials specified for many uses in the construction of the buildings. This practice resulted in at least two interrelated difficulties: First, an adequate definition of "noncombustible" was difficult to develop; and second, after several attempts at definitions, many materials with reduced fire hazards were restricted. Now, attention has been focused on the fact that fire is propagated by heat--propagation is controlled by generation, accumulation, and dissipation of heat.

Regulatory agencies are now starting to recognize "low combustibility" of some construction materials in relation to heat output per pound or per square foot of surface area. They have taken the position that heat output per unit of exposed area per unit of time (rate of heat release) would be the most appropriate basis to deal with these changes. Unfortunately, no test method is widely recognized for determining the rate of heat release although several types of equipment (with different procedures, including one at the Forest Products Laboratory), are being considered (1,2,5-7).² Because codes lack a suitable test method to measure rate of heat release, agencies for certain codes are considering the use of the National Bureau of Standards "potential heat" method (4) to define "low combustibility." This is essentially a total heat release method in which the total heat released by a material over a period of time can be determined. Therefore, paper, heavy timber, and fire-retardant-treated wood have almost the

same degree of hazard because they have approximately the same total heat content per pound. In actual fires, if the rate of heat release is slow, a much lower hazard exists than if the release rate is fast. For acceptance and safe use of wood products in buildings, it is important that adequate methods be available for measuring the rate of heat release (rather than the total heat release) and that data for wood and wood products and methods of improving products be obtained.

In developing a standard test method to measure rate of heat release, it was deemed desirable that an investigation be conducted in which a series of materials would be tested in several of the proposed types of equipment. This type of investigation was organized by Chamberlain, NFPA (National Forest Products Association) Research Associate, at the National Bureau of Standards. The work reported here is a comprehensive presentation and analysis of data obtained at the Forest Products Laboratory as a part of the Chamberlain investigation.

EQUIPMENT

The apparatus used to determine the rate of heat release for the FPL research consisted of a furnace in which one surface of the test material was exposed to fire (fig. 1, a), a fuel-air mixture supply stream (fig. 1, b) for an exposure burner within the furnace, and instrumentation to control and record various

¹The Laboratory is maintained in cooperation with the University of Wisconsin-Madison.

²Italicized numbers in parentheses refer to Literature Cited at end of this paper.

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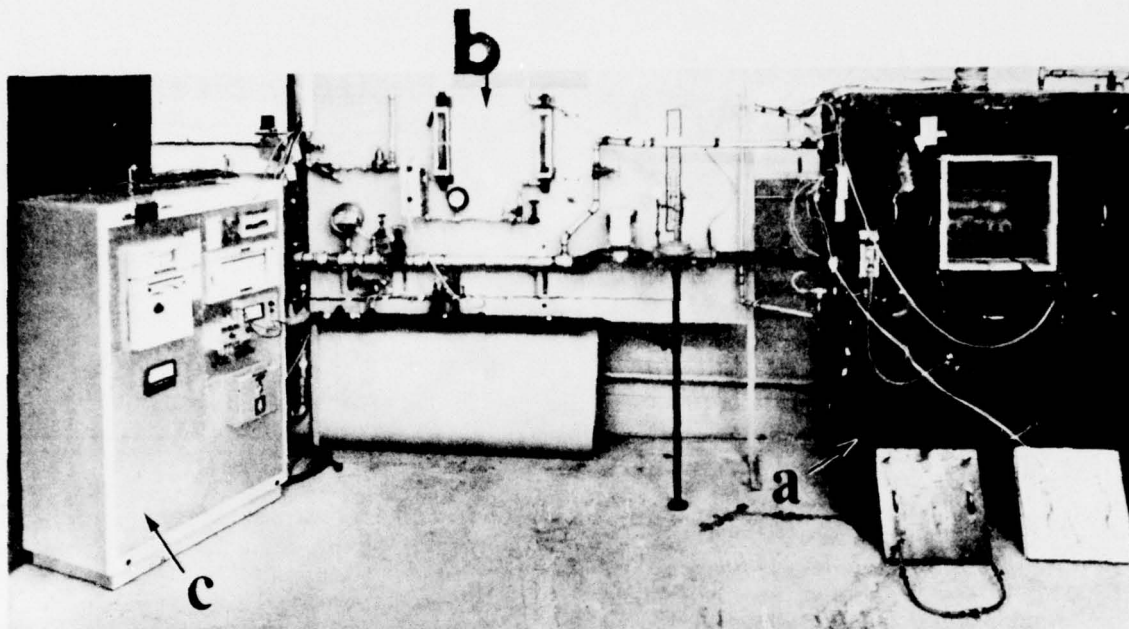


Figure 1.--Apparatus for measuring rate of heat release: Furnace, a; gas-air-water supply system, b; and electronic control cabinet, c.

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responses to the furnace operation (fig. 1, c). The equipment is described in detail in a previous publication (2).

The inside of the insulated furnace (fig. 1, a) was about 30 inches wide by 43 inches high by 17 inches deep. The front of the furnace had an 18- by 18-inch opening to accommodate a test specimen. An exhaust (or flue) at the top of the furnace was equipped with a wire mesh screen to improve gas flow patterns and attain better measurements of flue temperature. The flue temperature was measured using three, 20-gage, chromel-alumel thermocouples. The furnace was water jacketed; water that circulated in the jacket in the furnace walls absorbed heat that flowed from the hot furnace interior through the internal insulation. These wall heat losses could be measured from the temperature rise of the water.

A vertical exposure burner within the furnace was used to burn a premixed natural gas-air fuel mixture to provide the fire environment, or exposure, for the test specimens. Originally the four horizontal ducts, or manifolds, that form the burner were so arranged that 32 3/8-inch lava-tip burner nozzles were evenly distributed over the specimen surface

area. However, experience showed that the most uniform specimen temperature distribution was obtained if the nozzles in the top two horizontal manifolds were closed.

The ratio of air to natural gas was adjustable over a wide range by using a proportional mixer. An adjustment for outlet pressure was also provided. By varying the ratio of air to natural gas and the pressure at the mixer outlet, it was possible to produce a wide range of flame shapes, flame colors, and temperature-exposure conditions in the furnace. "Secondary air" to the furnace was supplied through a 1-inch pipe along the lower rear edge of the furnace interior. The secondary air can be contrasted to the "primary air," the air mixed with the natural gas fuel and burned by the exposure burner. The secondary air served two purposes: (1) Supplied oxygen for combustion of the test specimen, and (2) created a turbulence in the furnace interior that improved distribution of the temperature.

A water jacket for the specimen, a part of the water-circulating system, was constructed, and fits snugly in back of a specimen in the specimen opening. In figure 1, the jacket is shown on the floor at the left in front of the

furnace. The purpose of the jacket was to collect the heat transmitted through the back of the specimen that otherwise would be lost to the surrounding room. Water was circulated from the water jacket of the furnace through the specimen water jacket, then back to the water jacket of the furnace.

An 18- by 18-inch noncombustible blank specimen (fig. 1, on floor in front of furnace and to right of specimen water jacket) was used during furnace adjustments. The specimen was made of two sheets of asbestos mill-board, each 1/2 inch thick, with a 1/4-inch-thick layer of mineral wool insulation sandwiched between the sheets. To measure the exposure temperature distribution, chromel-alumel thermocouples were placed 1/4 inch in front of the fire-exposed surface at the corners and at the center of the blank specimen.

SPECIMEN PREPARATION

All specimen materials were conditioned at 80° F and 30 percent relative humidity for at least 6 weeks prior to testing. Some specimens for determining rate of heat release had to be fabricated and assembled. The exposed surface of each of these was 18 by 18 inches.

Douglas-fir lumber. -- This commercially available lumber (selected to be as free as possible from knots and other defects) was 1.5 inches thick and 7-1/4 inches wide. The fire test specimen was fabricated from 18-inch-long pieces of the lumber that were glued and clamped with phenol-resorcinol adhesive under room conditions. The resulting specimen was 18 by 18 by 1.5 inches. When determining rates of heat release, gluelines were horizontally oriented in the specimen opening of the furnace.

Medium-density hardboard. -- This commercially available hardboard was 3/8 inch thick.

Plywood (marine grade). -- This marine grade plywood was 3/4 inch thick, and made from Douglas-fir with a thermosetting adhesive. This plywood is manufactured to relatively close tolerances.

Gypsum wallboard wall assembly. -- This simulated wall assembly (fig. 2) was fabricated from 3/8-inch-thick gypsum wallboard on one face and three vertical (nominal 2- by 4-in.) Douglas-fir studs. One stud was mounted with its centerline corresponding to the specimen

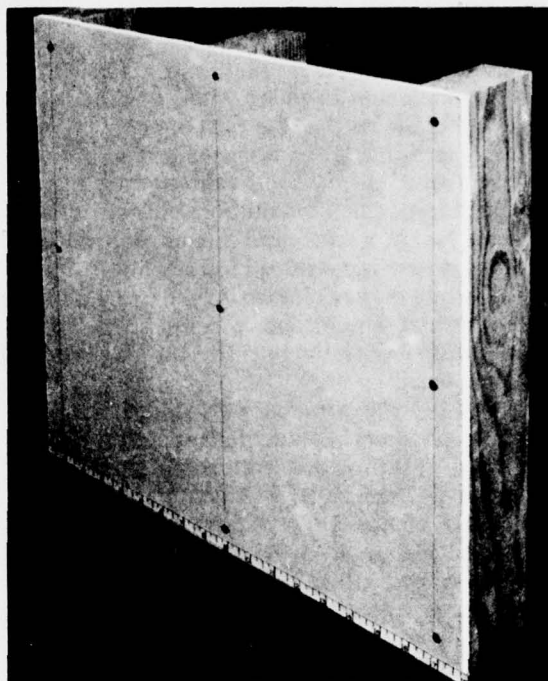


Figure 2.--Wall assembly of gypsum wallboard and Douglas-fir studs.

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centerline, whereas the two remaining studs were mounted with centerlines 8 inches on each side of the first centerline. Three 1-1/4-inch-long gypsum wallboard nails, 8 inches on center, were used to apply the gypsum wallboard to each stud. The back, or the unexposed side, had no facing, but during the fire test the usual 1/2-inch asbestos mill board was on this side to insulate against heat losses.

Fire-retardant-treated plywood. -- Samples of commercially available fire-retardant-treated Douglas-fir plywood, nominally 1/2-inch-thick, were obtained from two sources. The samples from both sources contained the same combination of water-soluble inorganic salts at 3.5 pounds per cubic foot of plywood.

RUN PROCEDURE

The method of determining heat release used here can be considered the "substitution method." This method is similar to the general procedure used by the Factory Mutual Engineering Division for their Construction Materials Calorimeter (7). A detailed description of the operating procedure is available (2).

In the substitution method, two determinations, or runs, are made for each test material: The first determination is made with the test specimen in place while a record is kept of the effects that the burning specimen has on the furnace flue temperature; and the second, with a noncombustible specimen and an additional "substitution burner" that supplies fuel at a measured rate to reproduce the first time-temperature relationship in the flue. The rate of heat release is then calculated as the rate at which heat is supplied by the substitution burner during the second determination.

Warming the furnace with the noncombustible specimen in place was the first step in both runs. This provided the furnace operating variables to stabilize to a steady state. Using flow rates of about 1.1 standard cubic feet of natural gas per minute, 30 standard cubic feet per minute of secondary air, and 1.6 gallons per minute (gal/min) of water, an average temperature of 800° F ($\pm 20^\circ$ F) was achieved at the corners of the noncombustible specimen. This was a temperature that would result in relatively short-time ignition of plywood, but was not excessive for convenient furnace operation. To assure complete burning of the natural gas, the proportional mixer was set to mix 10 volumes of air to 1 volume of natural gas and deliver the mixture at an outlet pressure of 2.5 inches of water. These settings are equivalent to 1,100 ± 50 Btu's per minute from the exposure burner. Experimental measurements showed that the resultant steady-state heat flux (radiative and convective) to the specimen varied over the specimen surface in the range of 1.5 to 3.0 watts per square centimeter (79-158 Btu/min/ft²).

A temperature rise of about 21° F (outlet minus inlet) was observed for the cooling water in the water jacket. The conclusion of the warm-up period was taken as the time when (1) the rise in temperature of the cooling water was constant with time (usually at about 21° \pm 1° F), (2) the furnace flue temperature was constant (usually at about 900 \pm 15° F), and (3) the temperatures at the corners of the exposed surface of the noncombustible specimen were relatively constant (usually at about 800° \pm 20° F).

The objective of the first run was to learn how the furnace would behave when the test material was burned. In this run, after the warm-

up, the noncombustible specimen was replaced with the test specimen as quickly as possible and with a minimum of disturbance to the exposure conditions. In mounting the specimens, a 1/2-inch-thick sheet of asbestos millboard was placed on the back of the specimen. The purpose was to reduce heat flow from the back of the specimen opening when the sample was consumed (under these exposure conditions all of the specimens were completely burned to ash). As the test specimen burned, recorder chart records were kept of the response of the furnace to the released heat. The response consisted of the temperature rise of the exhaust (flue) gases and of the cooling water.

The objective of the second run was to reproduce as closely as possible the conditions of the first, except, in place of the test specimen, propane-base fuel gas was fed into the furnace through an auxiliary or substitution burner. The substitution burner used was a 3-foot length of copper pipe with an inside diameter of 3/8 inch. The outlet of the pipe was at the bottom edge of the noncombustible specimen when in place in the furnace. When feeding in the fuel gas, of course, care was taken that the propane-base fuel was completely burned.

After warming the furnace to a steady state with conditions as similar as possible to those of the first run, the flow of propane-base fuel was begun. The flow was regulated by an operator so that the flue temperature-time relationship would be the same for the second run as for the first. During the second run, a record was kept of the propane fuel flow rate (ft³/min) at 1-minute intervals. The time variation of the rise in temperature of the cooling water was also observed and recorded.

The calculations are relatively simple. The uncorrected rate of heat release (Btu's per min) is determined by multiplying the propane-base fuel flow rate in standard cubic feet per minute by the fuel heat of combustion (2,516 Btu/std ft³). Although the flue-gas temperatures were regulated so that they were the same in the specimen and the substitution runs, slight differences occurred in the heat lost through the furnace walls that was measured by the data for the relationship of rise in cooling water temperature to time. These losses are computed on the basis of water-flow rate, specific heat, and temperature rise. Therefore, the previously mentioned rate of heat release values have been corrected by

using differences in losses in furnace wall heat between the first and second runs.

Finally, the specimen area (2.25 ft²) is taken into account so that the rate of heat release could be expressed in Btu's per minute per square foot of specimen surface area. Because the calculations make use of flow rates and temperature rises at the end of 1-minute intervals, the final results can be expressed as curves of rate of heat release (Btu/min/ft²) versus time (min).

RESULTS AND DISCUSSION

Rate of Heat Release

Rates of heat release for the wood products and the wood assembly are given in table 1. In general, the curves have some similar regions that can be discussed in terms of the specimen materials and the test method. After the specimens have been inserted in the furnace there is an initial "induction period" during which heat flows from the hot furnace interior to the relatively cool test material. The length of this period is related to the mass and the temperature of the original specimen, the efficiency of heat transfer, and the temperature that must be attained before active exothermic reactions can begin.

From most of the tested materials, the induction period was followed by a period of active, flaming combustion. During the active flaming period, pyrolysis products from the heated specimen travel to the area near the specimen surface, mix with an appropriate amount of air, and burn by flaming. This sequence can be used to explain why a peak in the heat release versus time curves frequently occurs (shortly after the induction period). Then a layer of hot char often forms at the surface of the specimen. This layer causes the rate of heat release to decrease by slowing the flow of heat to the cooler, unpyrolyzed, specimen interior and by slowing the flow of pyrolysis products from the specimen interior to the specimen surface. Occasionally, after the exposure had proceeded, specimens began to break and crumble. On breaking, of course, some relatively unpyrolyzed material was exposed; this caused an increasing rate of heat release (a peak) in the middle or near the end of a run.

Where duplicate runs were made, the range of values was about ± 10 percent of the mean.

Douglas-fir lumber.--The curves shown in figure 3 can be considered almost typical results for testing solid wood specimens in this apparatus (3). After the initial induction period, a peak of around 400 Btu's per square foot per minute is reached. Table 1 shows about 8 to 12 percent of the total area below the curve in the interval from 0 to 10 minutes. From 10 to about 35 minutes, there is evidence of a char layer buildup. The heat release rate is almost constant or decreases slightly. At about 40 to 50 minutes, deep cracks, or fissures, form in the char layer at the surface, and the specimen begins to crumble. On disintegration, fresh areas of relatively unpyrolyzed wood are exposed, and the surface area of the specimen is substantially increased. These factors lead to a substantial increase in the rate of heat release at almost 50 minutes from initial exposure of the specimen. Of course, in the first interval, the initial reaction of the specimen to fire exposure is flaming combustion (until about 10 min); in the second interval (to about 35 min), combustion is by both flaming and glowing while the specimen accumulates specific (sensible) heat. After the second interval (when the specimen has disintegrated), combustion is largely by glowing because no uncharred wood remains.

Medium-density hardboard.--By comparing curves in figure 4 with those in figure 3, it is easy to note the hardboard samples behave quite differently during fire exposure than does Douglas-fir lumber. These differences are attributable to effects of both sample composition and sample weight. Curves in figure 4 indicate that after the induction period, the initial (flaming) phase of combustion yields very high rates of heat release. Table 1 shows that about two-thirds of the total area below the curves occurs in the interval from the start of the test to about 10 minutes. After about 12 to 14 minutes the samples have disintegrated to form a pile of glowing material on the floor of the exposure furnace. The highest rates of heat release of any of the materials in this study were observed for these hardboard specimens.

Plywood (marine grade).--Marine grade plywood of Douglas-fir apparently behaves in a manner that may be characterized as "intermediate" between Douglas-fir lumber and medium-density hardboard. Curves in figure 5 show that after the original induction period, a short (2 min or so) flaming period is followed

Table 1. -- Rates of heat release for wood products and a wood assembly

Test specimen	Density	Maximum heat release rate	Time of maximum rate	Average rate (first 10 min)	Percent of total area below curve (first 10 min)
	Lb/ft ³	Btu/ft ² /min	Min	Btu/ft ² /min	Pct
Douglas-fir	30	524	46	217	7.9
lumber	33	490	54	266	11.6
Medium-density hardboard	38	1,032	10	628	62.7
	39	1,048	5	724	66.6
Plywood	34	861	24	226	15.5
(marine grade)	34	934	21	285	18.7
Gypsum wallboard wall assembly	--	95	83	0	0
Fire-retardant-treated plywood	40	466	20	0	0
(Source A)	39	336	22	0	0
(Source B)	38	362	20	7	1.1

by about 10 minutes with relatively low rates of heat release. During this time (from about 10 min to about 20 min) an insulating layer of char is accumulated, but the specimen continues to absorb and retain sensible heat. At about 20 minutes, fissures have developed in the char layer, and the specimen is about to collapse. When the specimen does break apart, momentarily high heat release rates are observed. From about 30 minutes on the specimen glows, and its remaining portion is consumed. Differences in curves between figure 5 and those in figure 3 are attributed almost entirely to the differences in sample thickness (1-1/2 in. for Douglas-fir lumber, 3/4 in. for plywood). Comparison of curves in figure 5 show that the results of duplicate runs for plywood were in good agreement.

Gypsum wallboard wall assembly.--The heat release rate versus the time curve for the assembly, figure 6, is significantly different from the curves discussed. No peak corresponds to flaming. After the start of the test, about 65 minutes were required before heat was released at an appreciable rate. During the previous period, heat was being absorbed by the assembly both in the form of sensible heat

and in the form of heat needed to calcine the gypsum in the wallboard. After this process is complete at about 65 minutes, the studs in the assembly are pyrolyzed, and the pyrolysis products diffuse (through cracks in the wallboard) into the hot furnace interior where they burned at a maximum rate of 90 to 100 Btu's per square foot per minute. It should be noted that the performance of the simulated wall assembly would be difficult to predict, based on the data for Douglas-fir lumber (fig. 3). The rate of heat release of assemblies is generally difficult to formulate from the rate of heat release of the assembly parts. The period after 100 minutes in figure 6 represents glowing combustion of the assembly.

Fire-retardant-treated plywood.--Although curves in figure 7 show a peak in about 20 to 22 minutes, which corresponds to the time for flaming combustion, the fire-retardant-treated plywood specimens were consumed largely by glowing. Peaks such as these did not appear in previous heat-release determinations on fire-retardant-treated plywood (3). The data indicated by these curves show that the fire-retardant treatment appreciably reduces rates of heat release, especially if

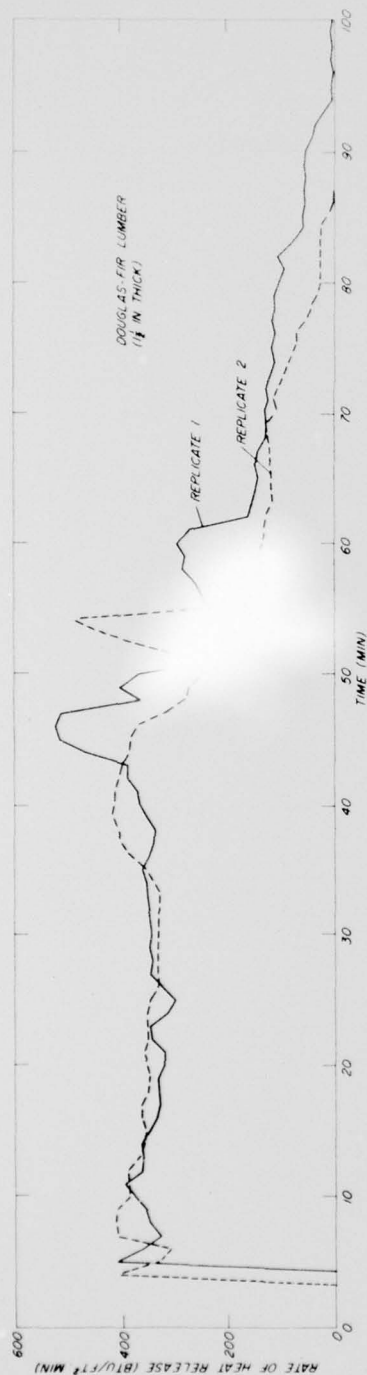


Figure 3.--Relationship of rate of heat release to time for Douglas-fir lumber 1-1/2 inch thick (replicates 1 and 2).
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curves in figure 7 are compared with those of figure 5. In addition, the treatment tends to lengthen the induction period, the period from initial exposure to the time rates of heat release begin to be measurable. The differences between fire-retardant-treated and untreated wood are additionally significant if differences in sample thicknesses are considered: The marine grade plywood (fig. 5) was 3/4 inch thick whereas the treated plywood was only 1/2 inch thick. Ordinarily, a decrease in sample thickness would be expected to be associated with a shorter induction period and generally higher initial rates of heat release. Thinner specimens, too, should tend to be totally consumed more quickly.

CONCLUSIONS

1. Characteristic curves for rate of heat release were obtained for an assortment of wood products exposed in the heat-release-rate calorimeter of the Forest Products Laboratory. The curves can be interpreted in terms of specimen geometry, specimen materials, and fire test exposure.

2. Fire-retardant treatment of plywood reduces rate of heat release in both the flaming and the glowing modes of combustion.

3. Predicting heat release rates from measurements of individual assembly components is difficult. The interactions between the various components during fire exposure are complex.

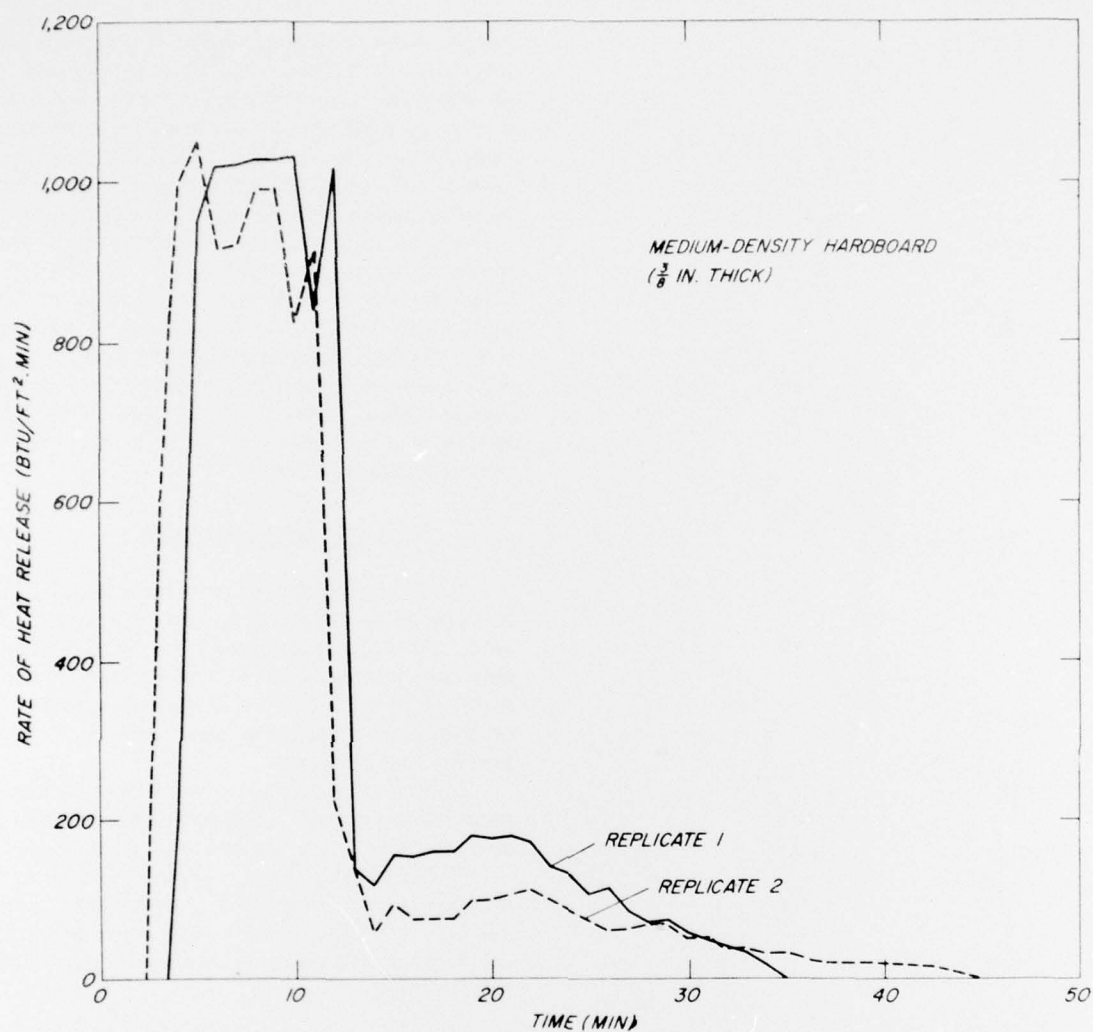


Figure 4.--Relationship of rate of heat release to time for medium-density hardboard, $\frac{3}{8}$ inch thick (replicates 1 and 2).

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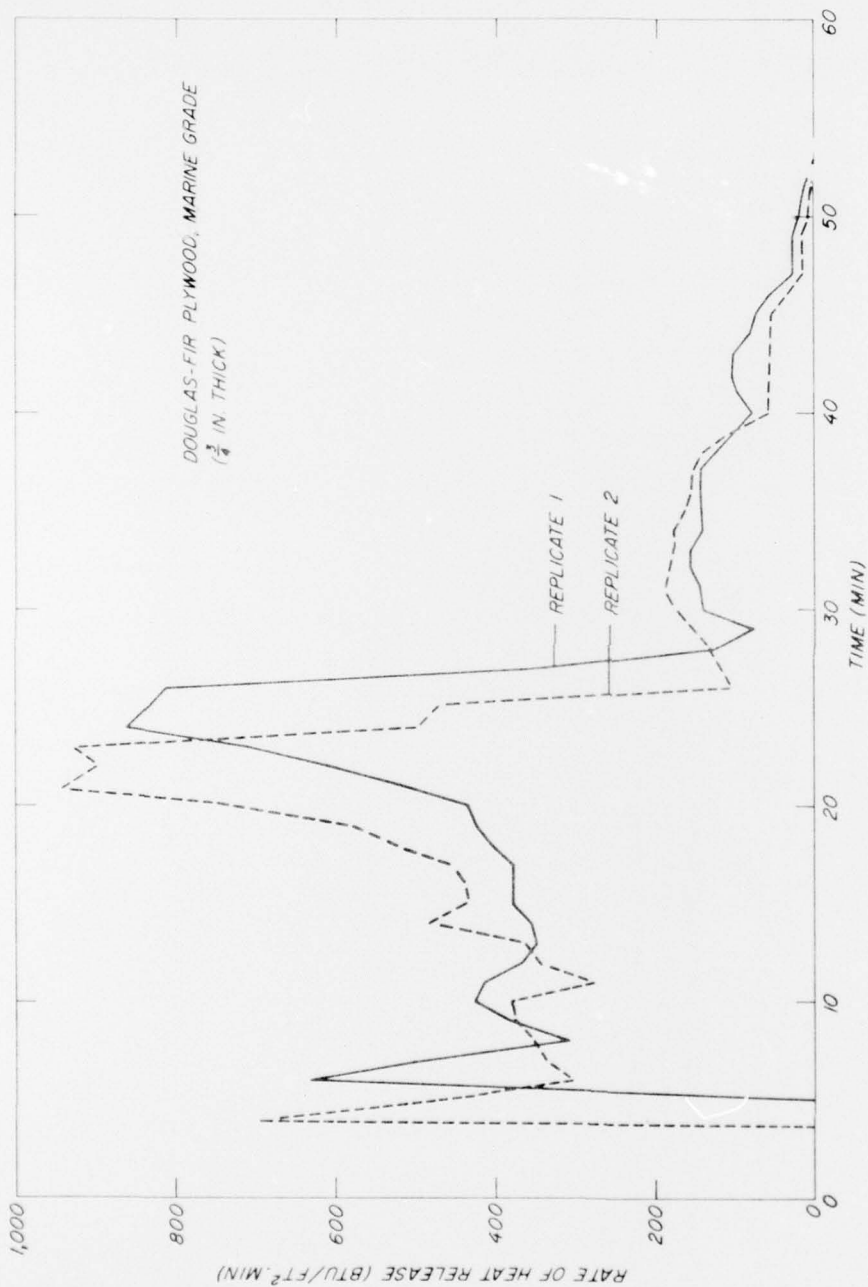


Figure 5.--Relationship of rate of heat release to time for marine grade Douglas-fir plywood, $\frac{3}{4}$ inch thick (replicates 1 and 2)
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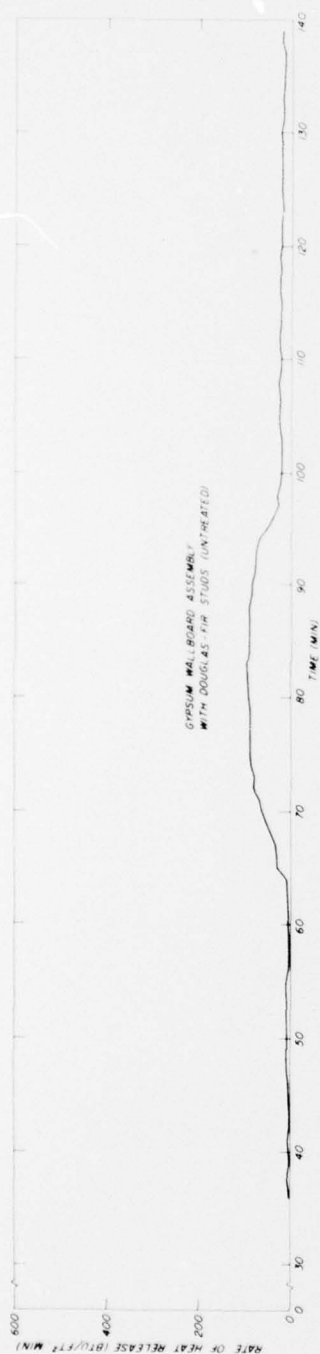


Figure 6.--Relationship of rate of heat release to time for a gypsum wallboard wall assembly with untreated Douglas-fir studs.
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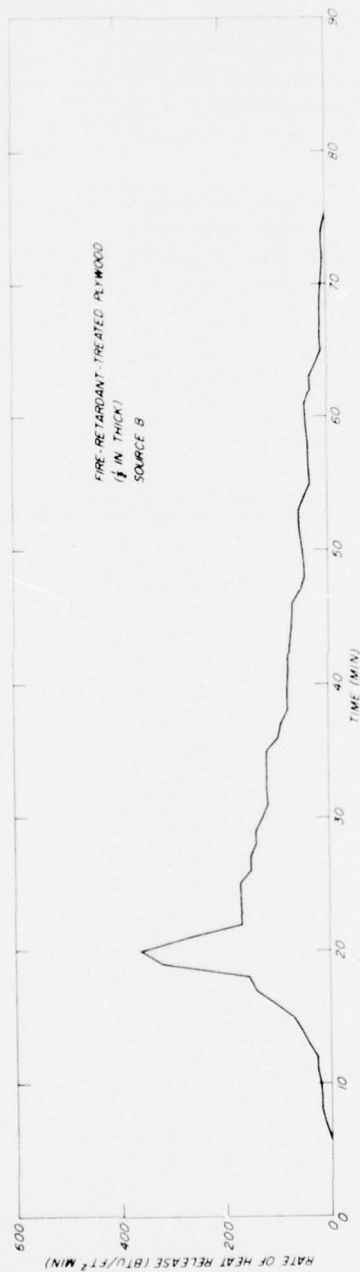
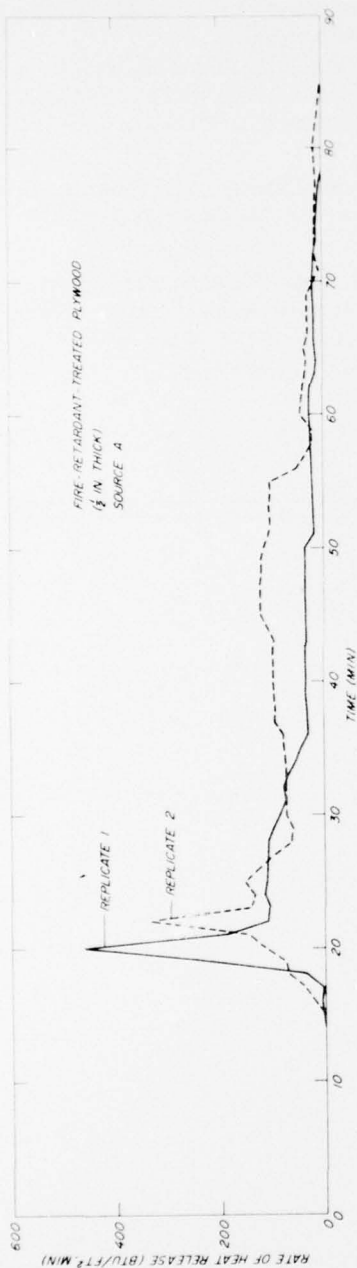


Figure 7.--Relationship of rate of heat release to time for fire-retardant-treated plywood, 1/2 inch thick (source A, replications 1 and 2 and source B).
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U.S. Forest Products Laboratory.

Measurements of heat release rates on wood products and an assembly, by John J. Brenden. Madison, Wis., For. Prod. Lab. 1977.

12 p. (USDA For. Serv. Res. Pap. FPL 281).

Rates of heat release for lumber, hardboard, plywood, and a wallboard assembly are determined with FPL-developed apparatus.

KEYWORDS: Rate of heat release, Douglas-fir, lumber, hardboard, marine grade plywood, wallboard assembly, fire-retardant-treatment.

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